

HEEGNER POINTS ON CARTAN NON-SPLIT CURVES

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ABSTRACT. Let E be an elliptic curve of conductor N , and let K be an imaginary quadratic field such that the root number of E/K is -1 . Let \mathcal{O} be an order in K and assume that there exists an odd prime p , such that $p^2 \parallel N$, and p is inert in \mathcal{O} . Then although there are no Heegner points in $X_0(N)$ attached to \mathcal{O} , in this article we construct such points from Cartan non-split curves. In order to do that we give a method to compute Fourier expansions for forms in Cartan non-split curves, and prove that the constructed points form a Heegner system as in the classical case.

INTRODUCTION

Let E be an elliptic curve over \mathbb{Q} of conductor N and let K be an imaginary quadratic field such that E/K has root number -1 . One of the main problems in number theory is to construct rational points on E . The only instance in which a general construction is known is via the so called “Heegner points”. Let \mathcal{O} an order in K of discriminant prime to N satisfying the *Heegner hypothesis*: “assume that all primes dividing N are split in \mathcal{O} ” (see [Dar04] Hypothesis 3.9). Then one can construct points in the modular curve $X_0(N)$ and map them through the modular parametrization to the curve E . Then Gross-Zagier theorem says that the constructed points are non-torsion if and only if $L'(E, 1) \neq 0$. It is important to remark that when N is square-free, Heegner’s hypothesis is the right one for the root number to be -1 , but when N is not square-free, this is not true. Nevertheless, this is still the right condition for the existence of Heegner points in the modular curve $X_0(N)$.

When N is not square-free, the situation is quite different. Suppose that we start with an elliptic curve E over \mathbb{Q} of conductor p^2 (p an odd prime). Let K an imaginary quadratic field with discriminant D such that D and p are prime to each other and p is inert in K . In this case the root number is still -1 , but the Heegner hypothesis is not satisfied. However, one would like to construct Heegner points in this case as well! Of course there will be no points in the classical modular curve $X_0(p^2)$, so one can search in other modular curves for the same phenomena. In the present

2010 *Mathematics Subject Classification.* Primary: 11G05, Secondary: 11F30.

Key words and phrases. Cartan Curves, Heegner points.

DK was partially supported by a CONICET doctoral fellowship.

AP was partially supported by CONICET PIP 2010-2012 GI and FonCyT BID-PICT 2010-0681.

situation, there are some canonical choices, the so called non-split Cartan curves, which are quotients of the Poincare half-plane by a Cartan non-split group. The two main problems one needs to address can be summarized with the following questions:

- There are many Cartan non-split curves (one for each non-square modulo p), which one should we choose? Is the elliptic curve E a quotient of their Jacobians?
- How to compute the Fourier expansion of the modular forms for such groups? What is the coefficient field of such forms?

In this article we will answer these questions, and show how to construct (both theoretically and computationally) Heegner points from points in Cartan non-split curves. We will show that they form the so called *Heegner systems* and satisfy the same properties as the ones coming from classical curves.

The present article is organized as follows: in the first section we recall the basic definitions of Cartan non-split curves, and give a moduli space interpretation for them. Our moduli problem is quite different from the classical ones and the one described in [RW14], but it makes the geometric and analytic properties of Hecke operators and Heegner systems more clear. For example, with this moduli interpretation it is easy to define Hecke operators (outside p), and show that the definition of modular forms for Cartan non-splits subgroups (as in [Che98]) is the same as the moduli interpretation one. It is also easily generalizable to more general conductors.

After giving the basics of modular forms for Cartan non-split groups, we move to the question of computing their q -expansions. We prove that such expansions have coefficients in $\mathbb{Q}(\xi_p)$ with a suitable normalization that we propose. We want to point out that we do not know a way for theoretically computing the q -expansion. Using our normalization, we compute it numerically (by solving a linear system) and once we know the coefficient field, we can compute it exactly. Furthermore, we only need to compute numerically one coefficient of the form (see the computational digression in Section 3). A Theorem of Chen and Edixhoven ([Che98, Edi96]) proves in this case that our curve is isogenous to a quotient of the Jacobian of the Cartan non-split curve, so one can use the Abel-Jacobi map to compute the modular parametrization. One big obstacle here is that the cusps for the Cartan non-split curves are not defined over \mathbb{Q} (implying the Abel-Jacobi map is not rational), so we average such maps over all the cusps, to get a rational map (which we also call the Abel-Jacobi map). The effect of averaging on Heegner points is the same as that of considering all the Cartan curves (for the different choices of a non-square modulo p), so an answer to our first question is that for constructing Heegner points one needs all the curves at the same time. It is a natural and interesting question to understand which is the Manin constant in our situation. At the time, we do not have an answer to this question (we give some examples at the end).

Once one understands the level p^2 case, it is natural to consider mixed cases, i.e. elliptic curves whose conductor is not square-free and an order in an imaginary quadratic field where some primes of the conductor are split and the other ones are inert. We consider this case as well, and there are no further difficulties than in the conductor p^2 case. Nevertheless, we believe that considering first the conductor p^2 case makes the big picture easier to understand.

The third and fourth sections are about constructing Heegner points in the general case. We first give some easy remarks on the Abel-Jacobi map and then show how our moduli interpretation allows to construct Heegner points and Heegner systems satisfying the usual compatibility relations. We end this article with a section of examples, where we show how the method works for different elliptic curves.

Acknowledgments: We would like to thank Professor Henri Darmon for many suggestions and for the discussions the first author had with him while visiting McGill University. We also would like to thank Professor Imin Chen for explaining us the technicalities of the definition of Hecke operators on Cartan non-split groups and Professor Tim Dokchitser for the results in Appendix A.

1. CARTAN NON-SPLIT CURVES OF PRIME LEVEL

1.1. Definition. Let ε be a fixed non quadratic residue modulo p . Let $C_{ns}^\varepsilon(p)$ the subgroup of $\mathrm{GL}_2(\mathbb{F}_p)$ given by the matrices of the form

$$C_{ns}^\varepsilon(p) = \left\{ \begin{pmatrix} a & b \\ b\varepsilon & a \end{pmatrix} \text{ such that } (a, b) \neq (0, 0) \right\}.$$

Given a matrix $A \in \mathrm{M}_{2 \times 2}(\mathbb{Z})$, we denote by \bar{A} its reduction mod p . Let $M_{ns}^\varepsilon(p)$ the suborder of $\mathrm{M}_{2 \times 2}(\mathbb{Z})$ given by

$$M_{ns}^\varepsilon(p) = \left\{ A \in \mathrm{M}_{2 \times 2}(\mathbb{Z}) : \bar{A} \in C_{ns}^\varepsilon(p) \cup \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \right\}.$$

Denote by Γ_{ns}^ε the elements in $M_{ns}^\varepsilon(p)$ with determinant 1. When it is clear from the context we will omit ε and p in the notation.

We can also consider the normalizer of the Cartan subgroup

$$C_{ns}^+(p) = \left\{ \begin{pmatrix} a & b \\ b\varepsilon & a \end{pmatrix} \cup \begin{pmatrix} a & b \\ -b\varepsilon & -a \end{pmatrix} \text{ such that } (a, b) \neq (0, 0) \right\},$$

and we can define $M_{ns}^+(p)$ and Γ_{ns}^+ as before.

Consider the extended Poincare half plane \mathcal{H}^* and its quotient $X_{ns} = \Gamma_{ns} \backslash \mathcal{H}^*$, which gives the Cartan non-split modular curve. It corresponds to the compactification of the curve $Y_{ns} = \Gamma_{ns} \backslash \mathcal{H}$. Analogously we can define $X_{ns}^+ = \Gamma_{ns}^+ \backslash \mathcal{H}^*$. Since $\mathrm{Det} : C_{ns}(p) \rightarrow \mathbb{F}_p$ is surjective, the modular curves $X_{ns}(p)$ and $X_{ns}^+(p)$ are defined over \mathbb{Q} .

1.2. Moduli interpretation. For our purposes we will only work with complex points of the Cartan curve, so we will state our moduli interpretation for them, but the same computations can be made over any scheme, and prove the existence of an integral model for Cartan non-split curves as well as their normalizers.

Consider pairs $[E, \phi]$, where E/\mathbb{C} is an elliptic curve and $\phi \in \text{End}_{\mathbb{F}_p}(E[p])$ satisfies that ϕ^2 is multiplication by ε . We say that two such pairs $[E, \phi]$, $[E', \phi']$ are isomorphic if there exists an isomorphism of elliptic curves $\Psi : E \rightarrow E'$ such that the following diagram is commutative.

$$\begin{array}{ccc} E[p] & \xrightarrow{\phi} & E[p] \\ \Psi \downarrow & & \downarrow \Psi \\ E'[p] & \xrightarrow{\phi'} & E'[p] \end{array}$$

Proposition 1.1. *The moduli problem of pairs $[E, \phi]$ as above is represented by the Cartan non-split curve Y_{ns}^ε . More concretely, the isomorphism class $\Gamma_{ns}^\varepsilon(p)\tau$ corresponds to the pair $[E_\tau, \phi_\tau]$ where $E_\tau = \mathbb{C}/\langle \tau, 1 \rangle$ and if $B_\tau = \left\{ \frac{1}{p}, \frac{\tau}{p} \right\}$ is a basis of $E_\tau[p]$ then ϕ_τ is the endomorphism of $E_\tau[p]$ whose matrix in the basis B_τ equals $\begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$.*

Proof. We need to check the following facts:

- The previous correspondence between points in Y_{ns}^ε and pairs $[E, \phi]$ is well defined.
- This map is bijective.

Let τ and τ' be elements in the upper half plane, which correspond to pairs $[E_\tau, \phi_\tau]$, $[E_{\tau'}, \phi_{\tau'}]$. If we prove that such pairs are isomorphic (with the previous identification) if and only if τ and τ' are equivalent under $\Gamma_{ns}^\varepsilon(p)$, we get that the map is well defined and injective.

It is a classical result that any morphism Ψ between two elliptic curves is given by multiplication by a complex number α . In particular, if Ψ is an isomorphism, $\alpha\langle \tau, 1 \rangle = \langle \tau', 1 \rangle$, so that there exists $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{SL}_2(\mathbb{Z})$ with $\alpha\tau = a\tau' + b$ and $\alpha = c\tau' + d$. From our moduli interpretation, we also need the map Ψ to satisfy $\phi_{\tau'}\Psi = \Psi\phi_\tau$. In the chosen basis, this implies checking that

- $\Psi(\phi_\tau(\frac{1}{p})) = \phi_{\tau'}(\Psi(\frac{1}{p}))$.
- $\Psi(\phi_\tau(\frac{\tau}{p})) = \phi_{\tau'}(\Psi(\frac{\tau}{p}))$.

An easy computation shows that

- $\Psi(\phi_\tau(\frac{1}{p})) = \Psi(\frac{\tau\varepsilon}{p}) = \frac{\alpha\tau\varepsilon}{p} = \frac{a\varepsilon\tau' + b\varepsilon}{p}$.
- $\Psi(\frac{1}{p}) = \frac{\alpha}{p} = \frac{c\tau' + d}{p}$, so $\phi_{\tau'}(\Psi(\frac{1}{p})) = \frac{c + d\varepsilon\tau'}{p}$.

We need equality to hold modulo $\langle 1, \tau' \rangle$, which implies that $a \equiv d \pmod p$ and $c \equiv \varepsilon b \pmod p$. In particular, the pairs $[E_\tau, \phi_\tau]$ and $[E_{\tau'}, \phi_{\tau'}]$ are isomorphic by a map satisfying the first condition if and only if τ and τ' are equivalent under $\Gamma_{ns}^\varepsilon(p)$.

The commutative condition for the second basis elements is similar and gives the same constraint.

Surjectivity follows from the following facts:

- Let $M \in \mathrm{GL}_2(\mathbb{F}_p)$ be such that $M^2 = \begin{pmatrix} \varepsilon & 0 \\ 0 & \varepsilon \end{pmatrix}$. Then there exists $A \in \mathrm{SL}_2(\mathbb{Z})$ such that $\bar{A}M\bar{A}^{-1} = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$. This will be proved in Lemma 1.2.
- Let $\phi \in \mathrm{End}_{\mathbb{F}_p}(E[p])$, and B, B' basis of $E[p]$. If $[\phi]_B$ denotes the matrix of ϕ in the basis B , and C the change of basis matrix from B to B' , then $[\phi]_B = C^{-1}[\phi]_{B'}C$ (this is just linear algebra).
- Let $[E, \phi]$ be a pair as before, let $\Psi : E \rightarrow E'$ be an isomorphism, B be a basis of $E[p]$, $B' = \Psi(B)$ be the image of such basis and ϕ' the element in $\mathrm{End}_{\mathbb{F}_p}(E'[p])$ making the diagram commute. Then $[\phi]_B = [\phi']_{B'}$.

Let $[E, \phi]$ be any such pair. Up to isomorphism, we can assume that $E = \mathbb{C}/\langle \tau, 1 \rangle$, where $\tau \in \mathcal{H}$. Let $B = \left\{ \frac{1}{p}, \frac{\tau}{p} \right\}$ be a basis of $E[p]$. By the first fact, there exists a matrix $A \in \mathrm{SL}_2(\mathbb{Z})$ such that $A[\phi]_B A^{-1} = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$. Then the other two facts prove that $[E, \phi] \simeq [\mathbb{C}/\langle A \cdot \tau, 1 \rangle, \phi']$, where $[\phi']_{\left\{ \frac{1}{p}, \frac{A \cdot \tau}{p} \right\}} = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$, which proves surjectivity. \square

Lemma 1.2. *Let $M \in \mathrm{GL}_2(\mathbb{F}_p)$ such that $M^2 = \begin{pmatrix} \varepsilon & 0 \\ 0 & \varepsilon \end{pmatrix}$, there exists $A \in \mathrm{SL}_2(\mathbb{Z})$ such that $\bar{A}M\bar{A}^{-1} = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$.*

Proof. Clearly there exists $B \in \mathrm{GL}_2(\mathbb{F}_p)$ such that $B^{-1}MB = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$. Consider the centralizer of $\begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$, which is given by C_{ns}^ε and take any matrix C of determinant $\det(B)^{-1}$ there. Then $BC \in \mathrm{SL}_2(\mathbb{F}_p)$ and has the same effect as B . The result follows from the fact that the reduction map $\mathrm{SL}_2(\mathbb{Z}) \mapsto \mathrm{SL}_2(\mathbb{F}_p)$ is surjective. \square

Remark 1.3. If we want to consider not the Cartan non-split but its normalizer, we consider pairs $[E, \phi]$ as before, but where two such pairs are isomorphic if $\Psi\phi = \pm\phi'\Psi$. It is clear that the same proof works and that we have an involution in X_{ns} given by sending $[E, \phi]$ to $[E, -\phi]$ whose fixed points are precisely X_{ns}^+ . We call this involution ω_p .

1.3. Modular Forms. As in the classical case, given a subgroup Γ of $\mathrm{SL}_2(\mathbb{Z})$, one can define what modular forms are for such group. Let $f : \mathcal{H} \rightarrow \mathbb{C}$ be an holomorphic function. If $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \Gamma$, and $k \in \mathbb{Z}$, we define the slash operator

$$f|_k \left[\begin{pmatrix} a & b \\ c & d \end{pmatrix} \right] (z) = (cz + d)^{-k} f \left(\frac{az + b}{cz + d} \right).$$

Then $M_k(\Gamma)$ is the space of holomorphic functions which are invariant under the previous action for all elements in Γ and which are holomorphic at the cusps. $S_k(\Gamma)$

is the subspace of cusp forms, which are those forms in $M_k(\Gamma)$ whose q -expansion at all cusps have zero constant coefficient.

We want to relate $S_2(\Gamma_{ns})$ to modular forms for classical subgroups. Clearly $\Gamma(p) \subset \Gamma_{ns}(p)$ so we have the reverse inclusion at the level of modular forms $S_2(\Gamma_{ns}(p)) \subset S_2(\Gamma(p))$. Let $\alpha_p = \begin{pmatrix} p & 0 \\ 0 & 1 \end{pmatrix}$. If $f \in S_2(\Gamma(p))$, $\tilde{f} = f|_2[\alpha_p]$ is a modular form for $(\alpha_p)^{-1}\Gamma(p)\alpha_p$. But if $M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$, then $\alpha_p^{-1}M\alpha_p = \begin{pmatrix} a & p^{-1}b \\ pc & d \end{pmatrix}$. So if $M \in \Gamma(p)$ we obtain that $(\alpha_p)^{-1}M(\alpha_p) \in \Gamma_0(p^2) \cap \Gamma_1(p)$ and conversely. Then slashing by the matrix α_p we obtain the isomorphism

$$(1) \quad S_2(\Gamma(p)) \cong S_2(\Gamma_0(p^2) \cap \Gamma_1(p)) = \bigoplus_{\chi} S_2(\Gamma_0(p^2), \chi),$$

where the sum is over all the even characters of conductor dividing p . Note that this is the same as summing over all characters which are squares so we also have

$$S_2(\Gamma_0(p^2) \cap \Gamma_1(p)) = \bigoplus_{\{\chi, \chi\chi_p\}} S_2(\Gamma_0(p^2) \otimes \chi)^{\text{new}} \oplus 2\left(\bigoplus_{\chi} S_2(\Gamma_0(p) \otimes \chi)\right)$$

where χ_p denotes the quadratic character of conductor p , and where the first sum is taken over pairs $\{\chi, \chi\chi_p\}$, where χ is any characters of conductor dividing p (but we do not want to count $\chi, \chi\chi_p$ twice), and the second sum is as before.

1.4. Hecke operators. There are two ways to define Hecke operators for classical subgroups. One of them is to define correspondences between the modular curves, and via the moduli interpretation translate this action to an action on modular forms, and the other one is in terms of double coset operators. We want to give this two interpretations in our setting, since each of them has its own advantages.

1.4.1. Geometric definition. Let n be a positive integer prime to p , and $[E, \phi]$ a pair as before, corresponding to the moduli interpretation of the curve Y_{ns}^ε . Define the Hecke operator

$$\mathcal{T}_n([E, \phi]) = \sum_{\psi: E \rightarrow E'} [E', \frac{1}{n}\psi \circ \phi \circ \hat{\psi}],$$

where the sum is over degree n isogenies $\psi: E \rightarrow E'$, and $\hat{\psi}$ denotes the dual isogeny. Note that since $\gcd(n, p) = 1$, $\frac{1}{n} \in \text{End}_{\mathbb{F}_p}(E'[p])$. Also, since $\psi \circ \hat{\psi}$ and $\hat{\psi} \circ \psi$ are multiplication by n , $(\frac{1}{n}\psi \circ \phi \circ \hat{\psi}) \circ (\frac{1}{n}\psi \circ \phi \circ \hat{\psi})$ equals multiplication by ε , so the points in the sum belong to Y_{ns}^ε .

1.4.2. *Algebraic definition.* We make a little survey of Hecke operators for the Cartan non-split curve, for which we follow closely Shimura's book ([Shi94]). Let

$$\Delta_p := \{A \in M_{2 \times 2}(\mathbb{Z}) : \det(A) > 0 \text{ and } \gcd(p, \det(A)) = 1\}.$$

Let Δ_{ns} be the intersection $\Delta_p \cap M_{ns}$, i.e. the set of matrices in M_{ns} with positive determinant relatively prime to p . Let $\Gamma(p)$ be the level p congruence subgroup, and let

$$\Delta(p) := \{A \in \Delta_p : \bar{A} \equiv \begin{pmatrix} 1 & 0 \\ 0 & * \end{pmatrix} \pmod{p}\}.$$

Let $R(\Gamma_{ns}, \Delta_{ns})$ and $R(\Gamma(p), \Delta(p))$ be the Hecke rings as defined in [Shi94] (page 54). We have the following Lemma.

Lemma 1.4. *The Hecke rings $R(\Gamma_{ns}, \Delta_{ns})$, $R(\mathrm{SL}_2(\mathbb{Z}), \Delta_p)$ and $R(\Gamma(p), \Delta(p))$ are isomorphic.*

Proof. Proposition 3.31 of [Shi94] proves that the last two ones are isomorphic. Clearly we have a map from $R(\Gamma_{ns}, \Delta_{ns})$ to $R(\mathrm{SL}_2(\mathbb{Z}), \Delta_p)$ given by $\Gamma_{ns}\alpha\Gamma_{ns} \rightarrow \mathrm{SL}_2(\mathbb{Z})\alpha\mathrm{SL}_2(\mathbb{Z})$. Surjectivity is proven in exactly the same way as the classical case. To prove injectivity, note that by Lemma 3.29, part (1) of [Shi94], if $\alpha \in \Delta_{ns}$, then

$$(2) \quad \Gamma_{ns}\alpha\Gamma_{ns} = \{\xi \in \mathrm{SL}_2(\mathbb{Z})\alpha\mathrm{SL}_2(\mathbb{Z}) : \bar{\xi} \in \overline{\Gamma_{ns}^\times \alpha}\}.$$

Then if $\alpha, \beta \in \Delta_{ns}$ are such that $\mathrm{SL}_2(\mathbb{Z})\alpha\mathrm{SL}_2(\mathbb{Z}) = \mathrm{SL}_2(\mathbb{Z})\beta\mathrm{SL}_2(\mathbb{Z})$, they have the same determinant, and by (2) $\Gamma_{ns}\alpha\Gamma_{ns} = \Gamma_{ns}\beta\Gamma_{ns}$. \square

If ℓ is a prime number different from p , then the Hecke operator $\mathcal{T}_\ell^\varepsilon$ is given by the action of the double coset $\Gamma_{ns}^\varepsilon\alpha\Gamma_{ns}^\varepsilon$, where $\alpha \in \Delta_{ns}$ is any matrix with determinant ℓ . In particular, if $\ell \equiv 1 \pmod{p}$, we can take $\alpha = \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix}$ and get the classical Hecke operator. By T_ℓ we will denote the Hecke operator acting on $S_2(\Gamma(p))$ and by \tilde{T}_ℓ the one acting on $S_2(\Gamma_0(p^2), \chi)$. Using the isomorphism (1), we get the following diagram

$$(3) \quad \begin{array}{ccc} S_2(\Gamma(p)) & \xrightarrow{|\alpha_p|} & \bigoplus_\chi S_2(\Gamma_0(p^2), \chi) \\ T_\ell \downarrow & & \downarrow \tilde{T}_\ell \\ S_2(\Gamma(p)) & \xrightarrow{|\alpha_p|} & \bigoplus_\chi S_2(\Gamma_0(p^2), \chi) \end{array}$$

Proposition 1.5. *Let ℓ be a prime congruent to 1 modulo p . Let $\gamma_i = \begin{pmatrix} 1 & i \\ 0 & \ell \end{pmatrix}$, $0 \leq i \leq \ell - 1$ and $\gamma_\infty = \begin{pmatrix} \ell c_1 & c_2 \\ p^2 \ell & \ell \end{pmatrix}$ be representatives for $\mathrm{SL}_2(\mathbb{Z}) \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \mathrm{SL}_2(\mathbb{Z})$ modulo $\mathrm{SL}_2(\mathbb{Z})$. (c_1 and c_2 are integers such that the matrix γ_∞ has determinant ℓ). Then $\{\alpha_p \gamma_i \alpha_p^{-1}\}_{i=0, \dots, \ell-1, \infty}$ is a set of representatives for $\Gamma_{ns} \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \Gamma_{ns}$ modulo Γ_{ns} .*

Proof. This is just an easy exercise. Note that $\alpha_p \gamma_\infty \alpha_p^{-1} \equiv \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \pmod{p}$. \square

Corollary 1.6. *If $\ell \equiv 1 \pmod{p}$, then the Hecke operators $\mathcal{T}_\ell^\varepsilon$ acting on $S_2(\Gamma_{ns}^\varepsilon)$ is the same as the Hecke operator T_ℓ acting on $S_2(\Gamma(p))$.*

Corollary 1.7. *If $\ell \equiv \pm 1 \pmod{p}$, then the Hecke operators $\mathcal{T}_\ell^\varepsilon$ acting on $S_2(\Gamma_{ns}^{+, \varepsilon})$ is the same as the Hecke operator T_ℓ acting on $S_2(\Gamma(p))$.*

Proof. This is because $\alpha = \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \in \Delta_{ns}^+$. \square

Let ℓ be a prime number different from p , and let $B \in \Delta_{ns}^\varepsilon$ be any matrix with determinant ℓ . Let $A_\ell^\varepsilon \in \mathrm{SL}_2(\mathbb{Z})$ be such that $A_\ell^\varepsilon \equiv B \begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix} \pmod{p}$. The action of A_ℓ^ε in $S_2(\Gamma(p))$ defines an operator that we will denote v_ℓ^ε . Note that such action does not depend on the choice of A_ℓ^ε , but only on B , since any two such matrices are equivalent modulo p .

Lemma 1.8. *The operator v_ℓ^ε is an isomorphism from $S_2(\Gamma_{ns}^\varepsilon)$ to $S_2(\Gamma_{ns}^{\varepsilon \ell^2})$ which does not depend on the choice of B .*

Proof. The first statement comes from the fact that $\bar{B} \in C_{ns}^\varepsilon(p)$, and the easy computation $\begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix}^{-1} C_{ns}^\varepsilon(p) \begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix} = C_{ns}^{\varepsilon \ell^2}(p)$. The second fact is immediate as well: if A_1 and A_2 are two matrices in $\mathrm{SL}_2(\mathbb{Z})$ corresponding to B_1 and B_2 , then $A_1 A_2^{-1}$ has determinant 1 and modulo p is in Γ_{ns}^ε , hence it acts trivially. \square

Proposition 1.9. *Let ℓ be a prime number different from p . Then $\mathcal{T}_\ell = T_\ell \circ v_\ell$.*

Proof. Let A_ℓ be as before. To compute the Hecke operator \mathcal{T}_ℓ , we need to find representatives for $\Gamma_{ns} \setminus (\Gamma_{ns} A_\ell \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \Gamma_{ns})$. Let $\{\gamma_i\}_{i=0, \dots, \ell-1, \infty}$ be the set of representatives for $\mathrm{SL}_2(\mathbb{Z}) \setminus (\mathrm{SL}_2(\mathbb{Z}) \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \mathrm{SL}_2(\mathbb{Z}))$. Then clearly the set $\{A_\ell \alpha_p \gamma_i \alpha_p^{-1}\}_{i=0, \dots, \ell-1, \infty}$ is a set of representatives for our quotient and for these representatives the statement is clear. \square

In particular, if $f \in S_2(\Gamma_{ns}^\varepsilon) \subset S_2(\Gamma(p))$, then $T_\ell(f) \in S_2(\Gamma_{ns}^{\varepsilon/\ell^2})$. Moreover, we have the following fact on these operators.

Proposition 1.10. *The operators $T_\ell : S_2(\Gamma_{ns}^\varepsilon) \rightarrow S_2(\Gamma_{ns}^{\varepsilon/\ell^2})$ and $v_\ell : S_2(\Gamma_{ns}^\varepsilon) \rightarrow S_2(\Gamma_{ns}^{\varepsilon \ell^2})$ are morphisms of Hecke modules.*

Proof. It is enough to prove that if $f \in S_2(\Gamma_{ns}^\varepsilon)$ is an eigenfunction for the Hecke operators, then $T_\ell(f) \in S_2(\Gamma_{ns}^{\varepsilon/\ell^2})$ is an eigenfunction for the Hecke operators with the same eigenvalues as f and that the same happens to the form $v_\ell(f) \in S_2(\Gamma_{ns}^{\varepsilon \ell^2})$.

Choose $\alpha \in \Delta_{ns}^\varepsilon$ of determinant q such that the entry $(2, 1)$ is divisible by ℓ . It is easy to see that T_ℓ restricted to $S_2(\Gamma_{ns}^\varepsilon)$ is equal to $\Gamma_{ns}^\varepsilon \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \Gamma_{ns}^{\varepsilon/\ell^2}$. Using Proposition

3.7 part (1) of [Shi94] we find that $T_\ell \mathcal{T}_q^\varepsilon = \Gamma_{ns}^\varepsilon \alpha \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \Gamma_{ns}^{\varepsilon/\ell^2}$. On the other hand, since $\alpha \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \ell \end{pmatrix} \alpha'$ with $\alpha' \in \Delta_{ns}^{\varepsilon/\ell^2}$ of determinant q , it follows by part (2) of the same proposition that $T_\ell \mathcal{T}_q^\varepsilon = \mathcal{T}_q^{\varepsilon/\ell^2} T_\ell$ which clearly implies the first part.

The proof of the second part is exactly the same, by noting that v_ℓ^ε is the double coset operator $\Gamma^\varepsilon A_\ell^\varepsilon \Gamma^{\varepsilon\ell^2}$. \square

Now we can prove the relation between the geometric and the algebraic definition of the Hecke operators.

Theorem 1.11. *The definition of Hecke operators acting as correspondences on the curve Y_{ns}^ε and that of double quotients agree.*

Proof. We just need to prove that the representatives used for one definition can be taken as representatives for the other one. For simplicity, we restrict to prime Hecke operators \mathcal{T}_ℓ . Recall that both definitions for the whole modular group $\mathrm{SL}_2(\mathbb{Z})$ do agree, so we can take as representatives for the degree ℓ isogenies the set $\{\frac{1}{\ell} \alpha_p \gamma_i \alpha_p^{-1}\}_{i=0, \dots, \ell-1, \infty}$. Then

$$\mathcal{T}_\ell([\mathbb{C}/\langle \tau, 1 \rangle, \phi_\tau]) = \sum_{i=0}^{\ell-1} [\mathbb{C}/\langle \frac{\tau+pi}{\ell}, 1 \rangle, \phi_i] + [\mathbb{C}/\langle \ell c_1 \tau + p c_2, p \ell \tau + \ell \rangle, \phi_\infty],$$

where $[\phi_i]_{\{\frac{1}{p}, \frac{\tau+pi}{\ell p}\}} = \begin{pmatrix} 0 & 1/\ell \\ \varepsilon \ell & 0 \end{pmatrix}$. To compute the upper half plane point, we need to compute the change of basis matrix taking ϕ_i to the form $\begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$. For $i = 0, \dots, \ell-1$, the matrix $\begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix}$ is such a matrix. Let $B \in \Delta_{ns}^\varepsilon$ be a determinant ℓ matrix, and $A_\ell \in \mathrm{SL}_2(\mathbb{Z})$ be such that $A_\ell \equiv B \begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix} \pmod{p}$ as before. Then $[\mathbb{C}/\langle \frac{\tau+pi}{\ell}, 1 \rangle, \phi_i] \simeq [\mathbb{C}/\langle \tau'_i, 1 \rangle, \phi_{\tau'_i}]$, where $\tau'_i = A_\ell \begin{pmatrix} 1 & pi \\ 0 & \ell \end{pmatrix} \tau$ and $[\phi_{\tau'_i}]_{B_{\tau'_i}} = \begin{pmatrix} 0 & 1 \\ \varepsilon & 0 \end{pmatrix}$ as we wanted.

For ϕ_∞ , $[\phi_\infty]_{\{\frac{\ell}{p}, \frac{\ell c_1 \tau}{p}\}} = \begin{pmatrix} 0 & 1/\ell \\ \varepsilon \ell & 0 \end{pmatrix}$ also, and the matrix $\begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix}$ takes this matrix to the standard form. Let $B \in \Delta_{ns}^\varepsilon$ as before, and $A_\ell \in \mathrm{SL}_2(\mathbb{Z})$ such that $A_\ell \equiv B \begin{pmatrix} 1 & 0 \\ 0 & 1/\ell \end{pmatrix} \pmod{p}$. Then $A_\ell \alpha_p \gamma_\infty \alpha_p^{-1}$ takes the pair to an upper half plane point with the required property. \square

Recall the following result by Chen and Edixhoven, which is crucial for this work. If \mathcal{C} is a curve, we denote by $\mathrm{Jac}(\mathcal{C})$ its Jacobian.

Theorem 1.12 (Chen-Edixhoven). *The Jacobian $\mathrm{Jac}(X_{ns}(p))$ is isogenous to the new part of the Jacobian $\mathrm{Jac}(X_0(p^2))$.*

Proof. See [Che98, Theorem 1] and [Edi96, Theorem 1.1]. \square

Remark 1.13. It can also be shown that this isogeny is stable under the Atkin-Lehner involution, meaning that forms in $S_2(\Gamma_{ns}^+(p))$ are in correspondence with newforms in $S_2^+(\Gamma_0(p^2))$.

In particular, if we start with a newform $g \in S_2(\Gamma_0(p^2))$ by the last Theorem there exists a modular form $f \in S_2(\Gamma_{ns}^\varepsilon(p))$ which has the same eigenvalues as g for all Hecke operators but p . We need to compute the Fourier expansion of f from that of g . Using such expansion, we can compute the modular parametrization needed for constructing Heegner points.

Let $f \in S_2(\Gamma_{ns}^\varepsilon(p))$ be an eigenform, and $g \in S_2^{new}(\Gamma_0(p^2))$ be the form with the same eigenvalues as f .

Theorem 1.14. *Let π_p the local automorphic representation of f at p . Then*

- *If π_p is supercuspidal, then $g \otimes \chi$ is a newform in $S_2(\Gamma_0(p^2), \chi^2)$ for all characters χ of conductor p and*

$$\tilde{f} = \sum a_\chi(g \otimes \chi),$$

where the sum is over all characters of conductor dividing p .

- *If π_p is Steinberg then there exists a newform $h \in S_2(\Gamma_0(p))$ such that $h \otimes \kappa_p = g$, where κ_p is the quadratic character of conductor p , and*

$$\tilde{f} = \sum a_\chi(g \otimes \chi) + ah,$$

where the sum is over all characters of conductor dividing p .

- *If π_p is Principal Series then there exists a non-quadratic character θ_p of conductor p and newforms $h \in S_2(\Gamma_0(p), \overline{\theta_p}^2)$, $\bar{h} \in S_2(\Gamma_0(p), \theta_p^2)$ such that $h \otimes \theta_p = g = \bar{h} \otimes \bar{\theta}_p$. Then*

$$\tilde{f} = \sum a_\chi(g \otimes \chi) + a_1 h + a_2 \bar{h},$$

where the sum is over all characters of conductor dividing p .

Before proving the Theorem, recall the following result, which is a consequence of Serre's open image theorem (or the Sato-Tate's conjecture).

Proposition 1.15. *Let $f \in S_2(\Gamma_0(p^2))$ be an eigenform, without complex multiplication. Then the set of primes ℓ satisfying $\lambda_\ell = 0$ has zero density. In particular, given any nonzero class $a \bmod p$ we can find a prime number ℓ such that $\ell \equiv a \bmod p$ and $\lambda_\ell \neq 0$.*

Proof of Theorem 1.14. Assume first that f does not have CM. Let χ a character of conductor dividing p , and let

$$F_\chi(f) = \sum_\ell \chi(\ell^{-1}) \frac{T_\ell(f)}{\lambda_\ell},$$

where the sum is over any set of representatives $\{\ell\}$ of elements in \mathbb{F}_p^\times satisfying $\lambda_\ell \neq 0$.

Claim: The sum does not depend on the choice of representatives.

Let ℓ, q be two relatively prime numbers such that $\ell \equiv q \pmod{p}$ and both λ_ℓ and λ_q are non-zero (which exists by Proposition 1.15). Then $\frac{T_\ell(f)}{\lambda_\ell}$ and $\frac{T_q(f)}{\lambda_q}$ are eigenforms for the Cartan $S_2(\Gamma_{ns}^{\varepsilon/q^2})$, and have the same Hecke eigenvalues, so from multiplicity one, one is a multiple of the other. Applying T_r where r is a prime such that $\lambda_r \neq 0$, $(r : \ell q) = 1$ and $r\ell \equiv 1 \pmod{p}$ and using that $T_{r\ell} = \mathcal{T}_{r\ell}$ we get the claim.

It is clear that the form f is a linear combination of the forms $F_\chi(f)$ (by the orthogonality relations of the characters), so we just need to relate the forms $F_\chi(f)|_2[\alpha_p]$ with the forms $g \otimes \chi$.

Let $q \neq p$ be any prime such that $\lambda_q \neq 0$. Without loss of generality, we can assume that ℓ is prime to q and that $\lambda_\ell \neq 0$. If this is not the case, we can choose $\ell' \equiv \ell \pmod{p}$ such that $\lambda_{\ell'} \neq 0$ and work with this prime instead. Using Diagram (3) we get

$$\begin{aligned} \tilde{T}_q(F_\chi(f)|_2[\alpha_p]) &= \sum_{\ell} \chi(\ell^{-1}) \tilde{T}_q \left(\frac{\tilde{T}_\ell(f)}{\lambda_\ell} \right) = \sum_{\ell} \chi(\ell^{-1}) \frac{\tilde{T}_q \tilde{T}_\ell(f)}{\lambda_\ell} = \\ &= \sum_{\ell} \chi(\ell^{-1}) \frac{\tilde{T}_{q\ell}(f)}{\lambda_\ell} = \chi(q) \lambda_q \sum_{\ell} \chi((q\ell)^{-1}) \frac{\tilde{T}_{q\ell} f}{\lambda_{q\ell}} = \chi(q) \lambda_q F_\chi(f)|_2[\alpha_p]. \end{aligned}$$

Then $F_\chi(f)|_2[\alpha_p]$ is an eigenform with the same eigenvalues as $g \otimes \chi$. If $\lambda_q = 0$, we want to prove that $T_q(F_\chi(f)) = 0$ as well. It suffices to show that in such case $T_q(f) = 0$. Suppose this is not the case, i.e. that $\lambda_q = 0$ but $T_q(f) \neq 0$. Let r be a prime such that $r \equiv q \pmod{p}$ and $\lambda_r \neq 0$. Then, by multiplicity one, there exists a constant c such that $cT_q f = T_r f$. Applying a proper Hecke operator as before, we get a contradiction.

Then $F_\chi(f)|_2[\alpha_p]$ is a form in $S_2(\Gamma_0(p^2) \cap \Gamma_1(p))$ with the same eigenvalues as $g \otimes \chi$. If $g \otimes \chi$ turns out to be a newform, then one is a multiple of the other and we are done. If $g \otimes \chi$ is not new (for some χ), then π_p corresponds to a ramified principal series (there are exactly two conjugated characters for which $g \otimes \chi$ is old) or π_p is Steinberg (in which case $g \otimes \chi_p$ is old). In both cases, there exists a form h as in the statement, such that $F_\chi(f)|_2[\alpha_p]$ is a linear combination of $h(z)$ and $h(pz)$. But $\langle h(z), h(pz) \rangle = \langle h(z), h \otimes 1_p \rangle$, where 1_p is the non-primitive trivial character of conductor p . (note that by hypothesis $h \otimes 1_p$ is a twist of g). In all cases, depending on the local type of the representation π_p , the statement follows.

If f has CM, then $f = f \otimes \chi_p$. In particular, if n is not a square modulo p , $a_n = 0$. On the contrary, if n is a non-zero quadratic residue modulo p , we can find, as before,

a prime ℓ such that $n \equiv \ell \pmod{p}$ and $\lambda_\ell \neq 0$. The same argument as in the previous case works, but considering the sum only over representatives of $\{\text{squares in } \mathbb{F}_p^\times\}$.

As before, it is easy to see that this definition does not depend on the representatives chosen and if we apply to this sum any T_n with n a non-square modulo p then $T_n F_\chi(f) = \lambda_n f = 0$, while if n is a square the same proof works. \square

Remark 1.16. If $f \in S_2(\Gamma_{ns}^{+, \varepsilon}(p))$ is an eigenform then $T_\ell f = \lambda_\ell f$ for $\ell \equiv -1 \pmod{p}$. In particular, if χ is an odd character, $F_\chi(f) = \sum_\ell \chi(\ell^{-1}) \frac{T_\ell(f)}{\lambda_\ell} = 0$, so all the non-zero coefficients in the linear combination of Theorem 1.14 are those corresponding to even characters.

Similarly, if $f \in S_2(\Gamma_{ns}^{-, \varepsilon}(p))$ (i.e. any matrix in the normalizer but not on the Cartan itself acts as -1), then it is easy to see that v_ℓ acts as -1 for $\ell \equiv -1 \pmod{p}$. Then $\lambda_\ell f = \mathcal{T}_\ell f = T_\ell v_\ell f = -T_\ell f$, which implies that $F_\chi(f) = \sum_\ell \chi(\ell^{-1}) \frac{T_\ell(f)}{\lambda_\ell} = 0$ whenever χ is even, so the non-zero coefficients in the linear combination of Theorem 1.14 are those corresponding to odd characters.

1.5. Fourier expansions. To compute the modular parametrization we need to compute the Fourier expansion, and find the appropriate normalization of it (which does not coincide with the one for classical modular forms). For that purpose we first need to understand the action of the Galois group $\text{Gal}(\mathbb{C}/\mathbb{Q})$ on modular forms.

For $a \in \mathbb{Q}^2$ and $z \in \mathcal{H}$ define

$$f_a(z) = \frac{g_2(z, 1)g_3(z, 1)}{\Delta(z, 1)} \wp(a \begin{pmatrix} z \\ 1 \end{pmatrix}; z, 1),$$

where $\wp(-; \omega_1, \omega_2)$ is the classical Weierstrass function associated to the lattice $L = \langle \omega_1, \omega_2 \rangle$, $g_2(L) = 60G_4(L)$, $g_3(L) = 140G_6(L)$ correspond to the lattice functions $G_{2n}(L) = \sum_{w \in L} \frac{1}{w^{2n}}$ (see Section 6.1 of [Shi94] for example). These functions satisfy $f_a(\gamma(z)) = f_{a\gamma}(z)$ for every $\gamma \in \text{SL}_2(\mathbb{Z})$. Let \mathcal{R}_p be the field of modular functions of level p , which by Proposition 6.1 of [Shi94] is

$$\mathcal{R}_p = \mathbb{C}(j, f_a \mid a \in (p^{-1}\mathbb{Z}^2)/\mathbb{Z}^2, a \notin \mathbb{Z}^2).$$

Let $\sigma \in \text{Gal}(\mathbb{C}/\mathbb{Q}(\xi_p))$. Since the functions j, f_a have Fourier expansions belonging to $\mathbb{Q}(\xi_p)$ we have that if $f = cj + \sum_a c_a f_a$,

$$\sigma(f) = \sigma(c)j + \sum_a \sigma(c_a) f_a.$$

Choose representatives β_j for $\pm\Gamma(p) \backslash \Gamma_{ns}^\varepsilon(p)$ such that $b \equiv 0 \pmod{\ell}$ (the number ℓ is auxiliary and we will choose it in different ways depending on our purpose). Then we can easily see that the field of modular functions for the non-split Cartan is the

subfield of \mathcal{R}_p given by

$$\mathcal{R}_{ns}^\varepsilon = \mathbb{C}(j, \sum_i f_{a\beta_i}).$$

Clearly it does not depend on the representatives chosen. Then to understand the action of $\text{Gal}(\mathbb{C}/\mathbb{Q})$ on modular forms for the Cartan subgroup, it is enough to understand the effect of $\text{Gal}(\mathbb{Q}(\xi_p)/\mathbb{Q})$ on them. Let ξ_p a fixed p -th root of unity, and consider the automorphism σ_ℓ given by $\sigma_\ell(\xi_p) = \xi_p^{\ell^{-1}}$. Extend this automorphism to \mathbb{C} and call it σ . By theorem 6.6 of [Shi94] and Theorem 3 (Chapter 6, section 3) of [Lan87] this automorphism acting on the meromorphic modular functions f_a , is given by $f_{a\alpha_{\ell-1}}$.

Proposition 1.17. *Let f be a meromorphic form of weight 0 for the Cartan group $\Gamma_{ns}^\varepsilon(p)$. Let $\sigma \in \text{Gal}(\mathbb{C}/\mathbb{Q})$ such that $\sigma = \sigma_\ell$ when restricted to $\mathbb{Q}(\xi_p)$. Then $\sigma(f)$ is a meromorphic form of weight 0 for $\Gamma_{ns}^{\varepsilon\ell^2}(p)$.*

Proof. Since f is a meromorphic form of weight 0, we have

$$f = \lambda j + \sum_a \lambda_a (\sum_i f_{a\beta_i}).$$

Then

$$\sigma(f) = \sigma(\lambda)j + \sum_a \sigma(\lambda_a) (\sum_i f_{a\beta_i\alpha_{\ell-1}}).$$

The action on each f_a can be written as $f_{a\beta_i\alpha_{\ell-1}} = f_{a\alpha_{\ell-1}(\alpha_\ell\beta_i\alpha_{\ell-1})}$. Since $(\alpha_\ell\beta_i\alpha_{\ell-1})$ are representatives for $\pm\Gamma(p)\backslash\Gamma_{ns}^{\varepsilon\ell^2}(p)$ we see that $\sigma(f)$ is an automorphic form for the required group. \square

Remark 1.18. Although the last result is only stated for weight 0 forms, it also applies to modular forms of other weights just by dividing the form by an appropriate Eisenstein series with rational Fourier coefficients.

If $f \in S_2(\Gamma_{ns}^\varepsilon)$ is an eigenform for the Hecke operators then we know that $\sigma(f) \in S_2(\Gamma_{ns}^{\varepsilon\ell^2})$. We want to prove that $\sigma(f)$ is an eigenform for its respective Hecke operators with Galois conjugate eigenvalues.

Proposition 1.19. *Let f be a meromorphic modular function for $\Gamma_{ns}^\varepsilon(p)$. Then $\sigma_q(v_\ell^\varepsilon(f)) = v_\ell^{\varepsilon q^2}(\sigma_q(f))$.*

Proof. Choose A_ℓ^ε in such a way that its $(1, 2)$ entry is divisible by q . It is easy to see that $\begin{pmatrix} 1 & 0 \\ 0 & q \end{pmatrix} A_\ell^\varepsilon \begin{pmatrix} 1 & 0 \\ 0 & 1/q \end{pmatrix}$, which belongs to $\text{SL}_2(\mathbb{Z})$ by our choice of A_ℓ^ε , gives the same action on the f_a as $A_\ell^{\varepsilon q^2}$ (since both matrices are easily seen to be equivalent modulo p). This proves the result on weight zero forms. For general weights, the same argument as in Remark 1.18 applies. \square

Corollary 1.20. *With the previous notation, $\mathcal{T}_q^{\varepsilon\ell^2}(\sigma_\ell(f)) = \sigma_\ell(\mathcal{T}_q^\varepsilon(f))$.*

Proof. This follows from the previous Proposition and the fact that σ_ℓ commutes with T_q (this is easily obtained by looking at the action on q -expansions). \square

Recall from Theorem 1.12 that the eigenforms in $S_2(\Gamma_{ns}^{\varepsilon\ell^2}(p))$ are in correspondence with forms in $S_2(\Gamma_0(p^2))^{new}$. The Galois group $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$ acts on $S_2(\Gamma_0(p^2))$ and commutes with Hecke operators. If σ is an element of such group and h is a modular form, we denote this action by h^σ .

If f is an eigenform in $S_2(\Gamma_{ns}^{\varepsilon\ell^2}(p))$ which corresponds to a form $g \in S_2(\Gamma_0(p^2))^{new}$, we denote by f^σ any non-zero eigenform that corresponds to the form g^σ .

Corollary 1.21. *With the previous notations, let $f \in S_2(\Gamma_{ns}^\varepsilon(p))$ be an eigenform. Then $T_\ell f = c\sigma_{\ell-1}(f^{\sigma_\ell})$.*

Proof. By Proposition 1.10, $T_\ell(f)$ is an eigenform in $S_2(\Gamma_{ns}^{\varepsilon/\ell^2}(p))$ with the same eigenvalues as f . By Corollary 1.20, $\sigma_{\ell-1}(f^{\sigma_\ell})$ is an eigenform whose eigenvalues are $\sigma_{\ell-1}$ applied to that of f^{σ_ℓ} , which equals that of f as well. The result now follows from multiplicity one. \square

With this setup we can give a first statement on the coefficient field of modular forms for the Cartan subgroup.

Theorem 1.22. *Let $f \in S_2(\Gamma_{ns}^\varepsilon)$ be a eigenform with the same rational eigenvalues for the Hecke operators as a newform $g \in S_2(\Gamma_0(p^2))$. Normalize \tilde{f} such that the first Fourier coefficient is rational. Then \tilde{f} (and f) have a q -expansion belonging to $\mathbb{Q}(\xi_p)$.*

Proof. Let $\ell \equiv 1 \pmod{p}$ a prime number such that $\lambda_\ell \neq 0$, and $\sigma \in \text{Gal}(\mathbb{C}/\mathbb{Q}(\xi_p))$ arbitrary. By Corollary 1.21 and the fact that $g^{\sigma_\ell} = g$ (so $f^{\sigma_\ell} = f$),

$$T_\ell f = c\sigma_{\ell-1}(f).$$

We know that $T_\ell f = \lambda_\ell f$, and if we look at the first Fourier coefficient (which is rational), we get that $c = \lambda_\ell$ and hence $f = \sigma_{\ell-1}(f)$. Since $\sigma_{\ell-1} \in \text{Gal}(\mathbb{C}/\mathbb{Q}(\xi_p))$ is arbitrary it follows that the q -expansion of f lies in the desired extension. \square

Remark 1.23. If we start with a newform g with coefficient field F , then the same result proves that the coefficient field of f is contained in $F(\xi_p)$.

Remark 1.24. By the orthogonality relations of the characters it follows that under the previous normalization, the coefficients of the linear combination of g of Theorem 1.14 satisfy that a_{χ_0} belongs to $\mathbb{Q}(\xi_p)$, and the rest belong to $\mathbb{Q}(\xi_p, \xi_{p-1})$.

1.6. Rational modular forms. The curve $X_{ns}(p)$ is defined over \mathbb{Q} and has $(p-1)$ cusps which are all defined over $\mathbb{Q}(\xi_p)$ and are Galois conjugate of each other (see [Ser97] Appendix 5). If $\sigma_\ell \in \text{Gal}(\mathbb{Q}(\xi_p)/\mathbb{Q})$, then there exists $A \in \text{SL}_2(\mathbb{Z})$ such that $\sigma_\ell(\infty) = A \cdot \infty$. The matrix A can be taken to be equal to A_ℓ^ε as defined before Lemma 1.8. Recall that if f is a weight k modular form, its Fourier expansion at the cusp A_ℓ^ε is given by the Fourier expansion of the form $f|_k[(A_\ell^\varepsilon)^{-1}]$ at the infinity cusp.

Let $\mathcal{F}_{ns}^\varepsilon$ be the field of rational meromorphic functions for the Cartan non-split group Γ_{ns}^ε , i.e. $\mathcal{F}_{ns}^\varepsilon := \mathbb{Q}(j, \sum_i f_{a\beta_i})$. Combining Proposition 1.17 with Lemma 1.8, it is easy to see that $\mathcal{F}_{ns}^\varepsilon$ consists of all meromorphic functions invariant for the Cartan non-split, whose q -expansion at infinity belongs to $\mathbb{Q}(\xi_p)$ and such that the Fourier expansion at $\sigma_\ell(\infty)$ equals $\sigma_{\ell^{-1}}(f)$. As in Remark 1.18, the same argument applies to other weights.

Definition 1.25. A form $f \in S_2(\Gamma_{ns}^\varepsilon(p))$ is called *rational* if its q -expansion at every cusp belongs to $\mathbb{Q}(\xi_p)$ and the expansion at the cusp $\sigma_\ell(\infty)$ equals that of $f|_2[(A_\ell^\varepsilon)^{-1}]$ at the infinity cusp.

Recall that if X is a curve defined over a field K , a differential form defined over K is a differential form which is locally of the form $f dg$, where f and g are meromorphic forms defined over K .

Proposition 1.26. *If $f \in S_2(\Gamma_{ns}^\varepsilon(p))$ is rational, it defines a rational meromorphic differential form $f(q) \frac{dq}{q}$ on $X_{ns}^\varepsilon(p)$, where $q = e^{\frac{2\pi iz}{p}}$.*

Proof. Note that

$$f(q) \frac{dq}{q} = \frac{2\pi i}{p} f(z) dz = \frac{f(z)}{\frac{pj'(z)}{2\pi i}} dj.$$

Since j belongs to $\mathcal{F}_{ns}^\varepsilon$ and $\frac{pj'}{2\pi i}$ is a rational weight 2 meromorphic for $\text{SL}_2(\mathbb{Z})$, their quotient lies in $\mathcal{F}_{ns}^\varepsilon$ as claimed. \square

Theorem 1.22 says that if f is an eigenform with rational eigenvalues, normalizing the form f in a way that its first coefficients is rational gives a form whose q -expansion belongs to $\mathbb{Q}(\xi_p)$, but if we multiply the form by any constant in such field, the same holds. So the problem is the following: what is the right way to normalize f ?

Theorem 1.27. *Let $f \in S_2(\Gamma_{ns}^\varepsilon)$ be an eigenform with rational eigenvalues. Then there exists a constant $c \in \mathbb{Q}(\xi_p)$ such that cf is rational.*

Proof. It is clear that c , if exists, is unique up to a rational constant. By Proposition 1.9, it is enough to prove that for all prime numbers ℓ

$$T_\ell(cf) = \lambda_\ell \sigma_{\ell^{-1}}(cf).$$

To prove existence, we consider two separate cases:

- If $a_{\chi_0} \neq 0$, it belongs to $\mathbb{Q}(\xi_p)$ by Remark 1.24, so we take $c = \frac{1}{a_{\chi_0}}$. We know that both $T_\ell f$ and $\sigma_{\ell^{-1}}(f)$ are forms in the same Cartan with the same eigenvalues for the Hecke operators outside p , so one is a multiple of the other, i.e. there exists a constant k such that

$$T_\ell f = k\sigma_{\ell^{-1}}(f).$$

Extend the automorphism $\sigma_{\ell^{-1}}$ to the extension $\mathbb{Q}(\xi_p, \xi_{p-1})$, trivially in ξ_{p-1} . By Theorem 1.14 $\tilde{f} = \sum a_\chi(g \otimes \chi) + a_1 h + a_2 \bar{h}$. Let μ_ℓ denote the eigenvalue of T_ℓ acting on h . Applying \tilde{T}_ℓ and $\sigma_{\ell^{-1}}$ to this equality we get

$$\begin{aligned} \sum_{\chi} a_\chi \lambda_\ell \chi(\ell) (g \otimes \chi) + \mu_\ell a_1 h + \bar{\mu}_\ell a_2 \bar{h} &= \tilde{T}_\ell \tilde{f} = k\sigma_{\ell^{-1}}(\tilde{f}) \\ k\sigma_{\ell^{-1}}(\tilde{f}) &= k \left(\sum_{\chi} \sigma_{\ell^{-1}}(a_\chi) (g \otimes \chi) + \sigma_{\ell^{-1}}(a_1) h + \sigma_{\ell^{-1}}(a_2) \bar{h} \right). \end{aligned}$$

Since the functions $g \otimes \chi, h, \bar{h}$ are linearly independent, the result follows by looking at the coefficient a_{χ_0} (which is rational and non-zero).

- If $a_{\chi_0} = 0$, the argument is a little more subtle. We start normalizing f such that its first non-zero coefficients is rational, so Theorem 1.22 implies that the q -expansion belongs to $\mathbb{Q}(\xi_p)$. We have that for each ℓ , there exists $c_\ell \in \mathbb{Q}(\xi_p)$ such that $T_\ell f = \lambda_\ell c_\ell \sigma_{\ell^{-1}}(f)$. We need to find a non-zero $c \in \mathbb{Q}(\xi_p)$ such that $T_\ell(cf) = \lambda_\ell \sigma_{\ell^{-1}}(cf)$, i.e. $c_\ell = \sigma_{\ell^{-1}}(c)/c$.

Let ℓ be a generator of \mathbb{F}_p^* such that $\lambda_\ell \neq 0$ (if g has CM take the square of a generator). Let ℓ_i , $1 \leq i \leq p-1$, be distinct primes in the same class of ℓ modulo p such that $\lambda_{\ell_i} \neq 0$. Then $\prod_{i=1}^{p-1} \ell_i \equiv 1 \pmod{p}$ and

$$(\prod \lambda_{\ell_i}) f = \mathcal{T}_{\prod \ell_i}(f) = T_{\prod \ell_i}(f) = T_{\ell_1} \circ \cdots \circ T_{\ell_{p-1}}(f) = (\prod \lambda_{\ell_i}) \text{Nm}(c_\ell) f.$$

Then $\text{Nm}_{\mathbb{Q}}^{\mathbb{Q}(\xi_p)}(c_\ell) = 1$ and by Hilbert theorem 90 there exists $c \in \mathbb{Q}(\xi_p)$ that satisfies $c_\ell = \sigma_{\ell^{-1}}(c)/c$. Since ℓ is a generator of \mathbb{F}_p^* it is easy to see that c satisfies $c_q = \sigma_{q^{-1}}(c)/c$ for every q . \square

Note that even for a rational modular form, it is not clear how to choose the rational multiple of it, which should correspond to “ $a_1 = 1$ ” in the classical case. The best one can do is to chose the coefficients to be algebraic integers and have no common rational integer factor.

Definition 1.28. Let $f \in S_2(\Gamma_{ns}^\epsilon)$ be a rational eigenform with rational eigenvalues. We normalize f such that the following properties hold:

- The Fourier expansion of f has algebraic integer coefficients.
- If $n \in \mathbb{Z}$ and $n \geq 2$, $\frac{f}{n}$ does not have integral coefficients.

Clearly there exists a unique (up to multiplying by -1) normalization satisfying the above conditions. The choice of the sign is not clear (see Remark 1.32).

If E' is an elliptic curve of conductor p^2 in the isogeny class associated to the newform g , we have the diagram

$$\begin{array}{ccc} X_{ns}^\varepsilon(p) & \hookrightarrow & \text{Jac}(X_{ns}^\varepsilon(p)) \\ & \searrow & \downarrow \\ & & \mathbb{C}/\Lambda_{E'} \end{array}$$

where the first map is the usual one, sending P to $(P) - (\infty)$. Note that this map is not defined over \mathbb{Q} , since the infinity cusp is defined over $\mathbb{Q}(\xi_p)$, and the other one is the usual quotient map (which is defined over \mathbb{Q}). If $\omega_{E'}$ is a holomorphic differential on $\mathbb{C}/\Lambda_{E'}$, then the pullback of the compositum is a constant multiple of $f(q)\frac{dq}{q}$ ($q = e^{\frac{2\pi iz}{p}}$) (by multiplicity one). Such constant will be called the Manin constant c_ε . This Manin constant satisfies $c_\varepsilon \Lambda_f = \Lambda_E$, where Λ_f is the lattice of periods associated to f and E is some curve in the isogeny class of E' . Such elliptic curve will be referred as the optimal quotient of $\text{Jac}(X_{ns})$.

Proposition 1.29. *The Manin constant is rational.*

Proof. Let $\sigma_\ell \in \text{Gal}(\mathbb{Q}(\xi_p)/\mathbb{Q})$, and consider the map from $X_{ns}^\varepsilon(p) \rightarrow \text{Jac}(X_{ns}^\varepsilon)$ given by $P \mapsto (P) - (\sigma_\ell(\infty))$. Then

$$\int_{\sigma_\ell(\infty)}^P f(q) \frac{dq}{q} = \int_\infty^{A_\ell^{-1}P} f|_2[A_\ell](q) \frac{dq}{q} = \int_\infty^{A_\ell^{-1}P} \sigma_\ell(f)(q) \frac{dq}{q}.$$

It is easy to see that the periods of f and $f|_2[A_\ell] \in S_2(\Gamma_{ns}^{\varepsilon\ell^2})$ are equal, so $c_\varepsilon = c_{\varepsilon\ell^2}$. This allows us to define another map by summing over all the conjugates, i.e. the map sending

$$P \mapsto \sum_{\sigma_\ell \in \text{Gal}(\mathbb{Q}(\xi_p)/\mathbb{Q})} (P) - (\sigma_\ell(\infty)).$$

Composing with the Abel-Jacobi map we get the map $AJ^\varepsilon : \text{Jac}(\mathcal{C}_{ns}^\varepsilon) \rightarrow E$ given by

$$(4) \quad AJ^\varepsilon(P) = \frac{2\pi i}{p} c_\varepsilon \left(\sum_{\sigma_\ell \in \text{Gal}(\mathbb{Q}(\xi_p)/\mathbb{Q})} \int_\infty^{A_\ell^{-1}P} \sigma_\ell(f^\varepsilon)(z) dz \right).$$

This map is clearly defined over \mathbb{Q} , and since both ω_E (the holomorphic differential form of the elliptic curve) and $f(q)\frac{dq}{q}$ are rational (by Proposition 1.26), the pullback $(AJ^\varepsilon)^*(\omega_E)$ is a rational multiple of $f(q)\frac{dq}{q}$ as claimed. \square

Remark 1.30. If $f \in S_2(\Gamma_{ns}^+)$, since the normalizer has $(p-1)/2$ cusps, all defined and conjugated over the maximal real subfield of $\mathbb{Q}(\xi_p)$, we will take the average in the Abel-Jacobi map over all such cusps.

Proposition 1.31. *With our normalization, the coefficients a_χ satisfy for all primes $\ell \neq p$ that $\sigma_{\ell-1}(a_\chi) = a_\chi \chi(\ell)$ where $\sigma_{\ell-1} \in \text{Gal}(\mathbb{Q}(\xi_p, \xi_{p-1})/\mathbb{Q}(\xi_{p-1}))$.*

Proof. Follows at once from Theorem 1.27. \square

Remark 1.32. Let $f \in S_2(\Gamma_{ns}^+)$. If $\ell \equiv -1 \pmod{p}$, σ_ℓ corresponds to complex conjugation in $\mathbb{Q}(\xi_p)$. Since the characters involved in the sum are even characters, $\chi(\ell) = 1$, and by the last Proposition σ_ℓ acts trivially. This implies that the coefficients of the modular forms in fact lie in $\mathbb{Q}(\xi_p + \xi_p^{-1}) = \mathbb{Q}(\xi_p^+)$. Similarly, if $f \in S_2(\Gamma_{ns}^-)$ the coefficients will be purely imaginary.

2. GENERAL LEVELS

In this section we generalize the previous results to more general conductors. Thanks to the Chinese Remainder Theorem, the theory works exactly the same as in the p^2 case. Let E/\mathbb{Q} be an elliptic curve of conductor N^2m with $\gcd(N : m) = 1$, and $N = p_1 \dots p_r$ (p_i distinct odd primes). By Shimura-Taniyama, it corresponds to an eigenform $g \in S_2^{\text{new}}(\Gamma_0(N^2m))$ with rational eigenvalues. Let ε_i be a non-square modulo p_i , for $i = 1, \dots, r$ and let $\vec{\varepsilon} = (\varepsilon_1, \dots, \varepsilon_r)$. Let $\Gamma_{ns}^{\vec{\varepsilon}}(N, m) = \cap_{i=1}^r \Gamma_{ns}^{\varepsilon_i}(p_i) \cap \Gamma_0(m)$ and consider the curve $\mathcal{C} = X_{ns}^{\vec{\varepsilon}}(N, m) = \Gamma_{ns}^{\vec{\varepsilon}}(N, m) \backslash \mathcal{H}^*$.

The moduli interpretation is a mixed of the classical one and the one of the previous section. We consider tuples $[E, \psi, \phi_1, \dots, \phi_r]$, where E/\mathbb{C} is an elliptic curve, $\psi : E \rightarrow E'$ is a cyclic degree m isogeny (or equivalently a cyclic subgroup of order m), and $\phi_i \in \text{End}_{\mathbb{F}_p}(E[p_i])$ is such that ϕ_i^2 corresponds to multiplication by ε_i for $i = 1, \dots, r$. A computation similar to that of Proposition 1.1 shows that \mathcal{C} represents the moduli problem stated.

We have the following generalization of Theorem 1.12.

Theorem 2.1. *$\text{Jac}(\mathcal{C})$ is isogenous over \mathbb{Q} to $\text{Jac}(X_0(N^2m))^{N^2\text{-new}}$.*

Proof. Let $X(Nm)$ be the modular curve which is the compactified moduli space of triples $(E/S/\mathbb{Q}, \phi)$, where S is a \mathbb{Q} scheme, E/S is an elliptic curve and $\phi : (\mathbb{Z}/Nm)_S^2 \rightarrow E[Nm]$ is an isomorphism of group schemes over S . The group $\text{GL}_2(\mathbb{Z}/Nm)$ acts on the right on $X(Nm)$. If Γ is any subgroup of $\text{GL}_2(\mathbb{Z}/Nm)$, one can consider the quotient $X(Nm)/\Gamma$ via an appropriate moduli interpretation. We are interested in the following two subgroups (as subgroups of $\text{GL}_2(\mathbb{Z}/Nm)$): $\Gamma_{ns}^{\vec{\varepsilon}}(N, m)$ and $\tilde{\Gamma} := \cap_{i=1}^r T(p_i) \cap \Gamma_0(m)$, where $T(p)$ is the standard maximal torus modulo p (consisting of diagonal matrices). The quotients correspond respectively to \mathcal{C} and $X_0(N^2m)$ (as in [Edi96], (1.0.4)).

Using an inductive argument, it is enough to prove that the Jacobian of the quotient by $\Gamma_1 = \cap_{i=1}^r T(p_i) \cap \Gamma_0(m)$ is isomorphic to the p_1 -new part of the quotient by $\Gamma_2 = \cap_{i=2}^r T(p_i) \cap \Gamma_0(p_1^2 m)$. But in this case, one can prove Proposition 1.2 of [Edi96] in exactly the same way, where now the subgroups of such paper correspond to the local components at p_1 of our subgroups (since both groups are the same at all the other primes). Then the same formalism as Theorem 1.3 (of [Edi96]) proves our claim. \square

The previous Theorem implies that there exists $f \in S_2(\Gamma_{ns}^\varepsilon(N, m))$ with the same eigenvalues for the Hecke operators as g outside the primes p_i . The theory works the same as in the level p^2 case, with some minor changes.

The geometric definition of Hecke operators is the same as before. We consider all degree n isogenies (for n prime to Nm) and consider the same action on each ϕ_i and, as in the classical case, the image of the cyclic subgroup by our isogeny.

The algebraic definition is also the same, and the operator v_ℓ , as well as coset representatives, are defined via a matrix $A \in \mathrm{SL}_2(\mathbb{Z})$ which satisfies the corresponding congruence modulo all the prime numbers p_i and such that they belong to $\Gamma_0(m)$.

Note that in particular $\sigma_{\ell-1}$ and T_ℓ will send modular forms for $\Gamma_{ns}^\varepsilon(N, m)$ to modular forms for $\Gamma_{ns}^{\varepsilon/\ell^2}(N, m)$, and all the results from the previous Section generalize trivially. In particular we have the analogue of Theorem 1.14.

Theorem 2.2. *Let $f \in S_2(\Gamma_{ns}^\varepsilon(N, m))$ be an eigenform. Then there exists eigenforms $h_i \in S_2(\Gamma_0(N_i m), \chi_i)$, with $N_i \mid N^2$, and χ_i a character of conductor N^2/N_i such that*

$$\tilde{f} = \sum a_\chi(g \otimes \chi) + \sum_i a_i^1 h_i + a_i^2 \bar{h}_i,$$

where the first sum is over all characters of conductor dividing N .

Proof. The proof is similar to that of Theorem 1.14. The CM case works exactly the same. If f does not have CM, we look at the local representation of our form g . Let p be a prime dividing N . If g is supercuspidal at p , then all of its twists by characters of conductor p have the same level as g (but with a character). If g is principal series or Steinberg at p , then there exists a twist by a character χ_p of it belonging to $S_2\left(\Gamma_0\left(\frac{N^2}{p}m, \chi_p^2\right)\right)$ (note that this is true locally, but since the class number of \mathbb{Q} is one, and there are no units, all local characters can be extended to global characters). Then we take $\chi_i = \prod_p \chi_p$ and h_i the new form attached to $g \otimes \chi_i$. Note that for each prime at which the representation is Principal Series we have two choices of the character (χ_p and $\bar{\chi}_p$) giving us also $\bar{\chi}_i = \prod_p \bar{\chi}_p$ and \bar{h}_i the newform associated to $g \otimes \bar{\chi}_i$. Now the same proof as in Theorem 1.14 applies. \square

Using this Theorem we can also compute the Fourier expansion as in the prime case. Now the q -expansion field will be $\mathbb{Q}(\xi_{p_1}, \dots, \xi_{p_r})$, whose Galois group is isomorphic to $\prod_i \mathbb{F}_{p_i}^\times$ and all the results work exactly the same. We take the same normalization as in the case of level p^2 . The Abel-Jacobi (as in (4)) map can be written in the form

$$(5) \quad AJ^{\vec{\varepsilon}}(\tau) = \frac{2\pi i}{N} c_{\vec{\varepsilon}} \sum_{\sigma \in \text{Gal}(\mathbb{Q}(\xi_N)/\mathbb{Q})} \int_{\infty}^{A_{\sigma}^{-1}\tau} \sigma(f^{\vec{\varepsilon}})(z) dz,$$

which implies summing the q -expansions over all the different Cartan non-split curves. Using the Fourier expansion for $f^{\vec{\varepsilon}}$, we can calculate the integral numerically to arbitrary precision. Recall that the convergence of such integral is exponential depending on the imaginary part of the point in the upper half plane. Finally we project into our elliptic curve using the Weierstrass uniformization.

We make the following observation about the Manin constant, which is supported by the evidence shown in the examples.

Conjecture 2.3. The Manin constant belongs to $\mathbb{Z}[1/N]$.

This conjecture should follow from similar arguments as exposed in [Maz78].

3. COMPUTATIONAL DIGRESSION

In order to compute explicitly the Fourier expansion of \tilde{f} , we need to write it as in Theorem 2.2. For that purpose, first we need to compute the local type of each prime dividing the conductor of E . This can be done either by looking at the reduced curve and the field where it gets semistable reduction or considering twists, as in [Pac13].

If there are some ramified principal series primes, one can compute the form h from the elliptic curve (see Appendix A).

Proposition 3.1. *Let $g_1, g_2 \in S_2(\Gamma_0(N^2m))$ be normalized newforms whose eigenvalues coincide in the set $\{n \in \mathbb{N} : n \equiv 1 \pmod{N}\}$. Then there exists $N' \mid N$ such that $g_1 = g_2 \otimes \chi_{N'}$.*

Proof. Suppose first that $N = p$ and $m = 1$. Let μ_n and λ_n the eigenvalues of g_1 and g_2 respectively. Furthermore assume that g_2 does not have CM (if it has CM the proof is similar).

Claim: $\mu_n = 0$ if and only if $\lambda_n = 0$. In particular this tells us that g_1 is not CM (since g_2 is not CM).

Proof of Claim: If $\mu_n = 0$ then by Proposition 1.15 we can find a prime $\ell \nmid n$, with $\ell n \equiv 1 \pmod{p}$ and $\lambda_{\ell} \neq 0$. Then $\lambda_{\ell} \lambda_n = \lambda_{\ell n} = \mu_{\ell n} = \mu_n \mu_{\ell} = 0$. Since λ_{ℓ} is not equal to zero it follows that $\lambda_n = 0$ as claimed.

For a a positive integer such that $\lambda_a \neq 0$, define the constant $c(a)$ such that $\lambda_a = c(a) \mu_a \neq 0$. The function $c(a)$ satisfies:

- (1) It depends only on a modulo p .
- (2) It is multiplicative, i.e. $c(a_1 a_2) = c(a_1) c(a_2)$.

To prove (1), let $a' \equiv a \pmod{p}$, so that $\lambda_{a'} = c(a') \mu_{a'}$. Fix such a' and choose ℓ such that $\mu_\ell \neq 0$, $(\ell : aa') = 1$ and $\ell a \equiv 1 \pmod{p}$. Then, as before, $\lambda_\ell \lambda_a = \mu_\ell \mu_a$, so $\lambda_\ell = c(a)^{-1} \mu_\ell \neq 0$. Similarly, $\lambda_\ell \lambda_{a'} = \mu_\ell \mu_{a'}$, so $\lambda_{a'} = c(a) \mu_{a'}$ as claimed.

To prove (2), we can assume that $\gcd(a_1, a_2) = 1$, and in this case, choosing n_1, n_2 inverses for a_1 and a_2 modulo p respectively with $\lambda_{n_i} \neq 0$, a similar computation gives the result.

In particular, if ℓ is a prime number which generates \mathbb{F}_p^* and such that $\lambda_\ell \neq 0$, $c(\ell^i) = c(\ell)^i$ implying that $c(\ell)$ is a $(p-1)$ -th root of unity. It is easy to see that this relation implies that g_2 is a twist of g_1 by a character of conductor dividing p . Since both are forms in $S_2(\Gamma_0(p^2))$ the only possibilities are $g_1 = g_2$ or $g_1 = g_2 \otimes \chi_p$ as claimed. The general case is an easy application of the Chinese Remainder Theorem. \square

Suppose we have all the forms of the linear combination of Theorem 2.2, and we need to find the coefficients in such combination in order for the form to be invariant under $\Gamma_{ns}^\varepsilon(N, m)$. These forms are clearly invariant under $\Gamma(N) \cap \Gamma_0(m)$, so we have to ask for invariance under $\Gamma_{ns}^\varepsilon(N, m) / (\Gamma(N) \cap \Gamma_0(m))$. For each prime p dividing N we have that $\Gamma_{ns}(p) / \Gamma(p) \cong \mathbb{Z} / (p+1)$. Then, by the Chinese Remainder Theorem we have that $\Gamma_{ns}^\varepsilon(N, m) / (\Gamma(N) \cap \Gamma_0(m)) \cong \prod_{p|N} \mathbb{Z} / (p+1)$. Choose generators for that group and several points in Poincare's upper half plane. We know that \tilde{f} is invariant for those matrices (conjugated by α_N^{-1}), so we evaluate h and its twists at the chosen points and impose these extra invariance conditions (which corresponds to a linear system). What is the dimension of this invariant subspace?

Proposition 3.2. *Suppose that g has no CM, and let a, b, c be the number of primes p dividing N such that the corresponding local representation π_p is: supercuspidal, ramified principal series or Steinberg respectively. The subspace of forms invariant for the Cartan is of dimension 2^{a+b} .*

Proof. Since all the forms in the linear combination of Theorem 2.2 are eigenforms with the same Hecke eigenvalues in the set $\{n \in \mathbb{N} : n \equiv 1 \pmod{N}\}$, Proposition 3.1 tells us that the eigenforms which are solution of our linear system are g and its quadratic twists. Let p be a prime dividing N . If π_p is supercuspidal or ramified principal series then both g and $g \otimes \chi_p$ are newforms with the same level, so we have a dimension 2 subspace. If π_p is Steinberg then $g \otimes \chi_p$ is not new, so we can distinguish between g and $g \otimes \chi_p$. Applying these observations to each prime dividing N the result follows by the Chinese Remainder Theorem. \square

Suppose the form g has some supercuspidal or ramified principal series primes. Then we want to compute the 1- dimensional subspace of f . Here is a way to do it:

- Suppose that π_p is supercuspidal. Let ϵ_p denote the local sign at p .

Claim: if $\epsilon_p = 1$ then in the linear combination of Theorem 2.2 for g only twists of g with characters having even p -part are involved, while for $g \otimes \chi_p$ only twists of g by characters with odd p -part are involved. If $\epsilon_p = -1$, the situation is the opposite one.

Proof of claim: Recall from Remark 1.16 that if $\epsilon_p = 1$ (resp. $\epsilon_p = -1$) then only twists of g with even p -part (resp. odd p -part) are in the sum. By Corollary 3.3 of [Pac13], the local sign at p changes while twisting g by χ_p like $-\left(\frac{-1}{p}\right) = -\chi_p(-1)$. Then the variation of the sign at p of the characters involved in the combination for g and $g \otimes \chi_p$ (as twists of g and $g \otimes \chi_p$) is opposite to the sign of χ_p , so if we write them as twists only of g , the signs at p are different.

- Suppose π_p is Principal Series. Let q be a non-square modulo p . Then the operator $T_q v_q / \lambda_q$ is an involution on the invariant subspace. Furthermore, it acts as $+1$ in the subspace spanned by (the form attached to) g and as -1 in the subspace spanned by $g \otimes \chi_p$. So, applying this operator we can get a 1-dimensional subspace as well.

To compute the 1-dimensional subspace, we take a non-trivial approximate solution for it and normalize as previously explained. Since we know that the first coefficient of the Fourier expansion lies in $\mathbb{Q}(\xi_N)$, we recover the exact such value from the approximate one. Recall that such coefficient is given by $\sum_{\chi} a_{\chi}$ (since g is normalized to start with q^1). Then if $p_i \nmid n$, the n -th coefficient of \tilde{f} is given by

$$(6) \quad a_n(g) \sum_{\chi} a_{\chi} \chi(n) = a_n(g) \sigma_{n-1} \left(\sum_{\chi} a_{\chi} \right),$$

where the last equality comes from Proposition 1.31. This gives the exact Fourier expansion, since we can also compute the coefficient at the various p_i^{α} . Note that the last sum of (6) only depends on n modulo $\prod p_i = N$, so we only compute it once for the $\phi(N)$ relatively prime to N remainders.

4. HEEGNER POINTS ON GENERAL CARTAN NON-SPLIT CURVES

Let E be an elliptic curve of conductor $N^2 m$ as before, with $N \neq 1$, and let $\mathcal{O} = \langle 1, \omega \rangle$ be an order in an imaginary quadratic field K which satisfies:

- The discriminant d of \mathcal{O} is prime to Nm .
- Every prime that divides m is split in \mathcal{O} .
- Every prime that divides N is inert in \mathcal{O} .

In particular, \mathcal{O} satisfies the classical Heegner hypothesis at the primes dividing m but not at the primes dividing N . We call such condition the *Cartan Heegner hypothesis* at (N, m) .

Remark 4.1. If we want to construct Heegner points for \mathcal{O} in the curve $X_0(N^2m)$, we need points fixed by a matrix M in $M_0(N^2m)$ with the same trace and determinant as ω , but under our hypothesis, there are no such matrices (by looking modulo p for any prime p dividing N).

A Heegner point for $\mathcal{C} = X_{ns}^\varepsilon(N, m)$ is a point τ in the upper half plane which is fixed by a matrix M in $M_{ns}^\varepsilon(N) \cap M_0(m)$ giving an embedding of \mathcal{O} into $M_{ns}^\varepsilon(N) \cap M_0(m)$, i.e. it satisfies

- $\text{Tr}(\omega) = \text{Tr}(M)$.
- $\text{Nm}(\omega) = \det(M)$.

Then τ is a fixed point by the usual action of this matrix group in the upper half plane. Each Heegner point τ gives rise to a pair of conjugate points (under the generator of the Galois extension $H/\mathbb{Q}(j(E_\tau))$) in $X_{ns}^\varepsilon(N, m)(H)$, where H is the Hilbert class field corresponding to \mathcal{O} and E_τ is the elliptic curve $\mathbb{C}/\langle 1, \tau \rangle$. For the details of this construction see [Ser97] (appendix A.5). Then if we apply the Abel-Jacobi map (5), we get a point in $E(K)$.

4.1. Heegner systems. For constructing systems of Heegner points, it is also useful to have a definition of Heegner points in terms of the moduli interpretation. For the Cartan non-split curve $\mathcal{C}_{ns}^\varepsilon(p)$, it is given by the following.

Definition 4.2. A Heegner point is a triple $(\mathcal{O}, [\mathfrak{a}], \phi_\alpha)$, where \mathcal{O} is as before, $[\mathfrak{a}]$ is an element in $\text{Pic}(\mathcal{O})$ which determines an elliptic curve $E_{\mathfrak{a}}$ with CM by \mathcal{O} , and ϕ_α is an element of $\text{End}_{\mathbb{F}_p}(E_{\mathfrak{a}}[p])$ such that:

- ϕ_α^2 is given by multiplication by ε .
- There exists $\alpha \in \mathcal{O}$ such that ϕ_α is given by multiplication by α .

Remark 4.3. The element α is well defined modulo p , which is an inert prime of \mathcal{O} , so we can just take $\alpha \in \mathcal{O}/p$.

For general levels, one considers tuples $[\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, \alpha]$, where for all primes $p \mid N$, multiplication by α in $E_{\mathfrak{a}}[p]$ satisfies the condition of the previous definition, and \mathfrak{m} is an ideal in \mathcal{O} of norm m and such that \mathcal{O}/\mathfrak{m} is cyclic. Note that giving the element α is the same as giving for each $p \mid N$ an endomorphism like in Definition 4.2, by the above remark and the Chinese Remainder Theorem.

Proposition 4.4. *Let $[\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, \alpha]$ be a Heegner point.*

- (1) *If τ denotes complex conjugation, then $(\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, \alpha)^\tau = (\mathcal{O}, [\mathfrak{a}^{-1}], \overline{\mathfrak{m}}, -\alpha)$*
- (2) *Let $[\mathfrak{b}]$ be a fractional ideal, and $\sigma_{\mathfrak{b}} \in \text{Gal}(H/K)$ the Artin symbol associated to $[\mathfrak{b}]$. Then*

$$(\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, \alpha)^{\sigma_{\mathfrak{b}}} = (\mathcal{O}, [\mathfrak{a}\mathfrak{b}^{-1}], \mathfrak{m}, \alpha)$$

- (3) *If $p \mid N$, then $\omega_p(\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, \alpha) = (\mathcal{O}, [\mathfrak{a}], \mathfrak{m}, -\alpha)$.*

Proof. The items (1) and (2) follow from [Ser67] (since \mathfrak{m} and α are defined over K), while (3) follows from Remark 1.3. \square

Using the geometric interpretation of Hecke operators as described in section 1.4.1 it is clear that we have the following formula for Hecke operators (for $\ell \nmid Nm$) acting on Heegner points, analogous to the one given in [Gro84] (section 6):

$$(7) \quad \mathcal{T}_\ell([\mathcal{O}, \mathfrak{a}, \mathfrak{m}, \alpha]) = \sum_{\mathfrak{a}/\mathfrak{b} \cong \mathbb{Z}/\ell} (\text{End}(\mathfrak{b}), \mathfrak{b}, \mathfrak{m} \cdot \text{End}(\mathfrak{b}) \cap \text{End}(\mathfrak{b}), \alpha).$$

Heegner points are constructed from orders in imaginary quadratic fields satisfying the Cartan Heegner hypothesis at (N, m) . But such orders are indexed by positive integers n (the conductor of the order). Let \mathcal{O}_n be the order of conductor n in K , and let K_n be its Hilbert class field. Recall that if $n_1 \mid n_2$, $\mathcal{O}_{n_2} \subset \mathcal{O}_{n_1}$ and $K_{n_1} \subset K_{n_2}$, in particular if P_1 is a Heegner point attached to \mathcal{O}_{n_1} and P_2 is a Heegner point attached to \mathcal{O}_{n_2} , there should be some relation between these two points (which lie in $E(K_2)$).

To define a *Heegner system* we follow [Dar04] (Definition 3.12).

Definition 4.5. A *Heegner system* attached to (E, K) is a collection of points $P_n \in E(K_n)$ (with n prime to Nm) satisfying the following properties:

- (1) Write $n = \ell m$, with ℓ a prime number inert in K , and consider a Heegner point P_n associated to \mathcal{O}_n . Then there exists a Heegner point P_m associated to \mathcal{O}_m such that

$$\text{Tr}_{K_n/K_m} P_n = \mathcal{T}_\ell P_m.$$

Moreover, if Q_n and Q_m denote the images of P_n and P_m under the modular parametrization, we have

$$\text{Tr}_{K_n/K_m} Q_n = a_\ell Q_m,$$

where a_ℓ is the ℓ -th coefficient of $L(E, s)$.

- (2) Let τ denote complex conjugation. Then there exists $\sigma \in \text{Gal}(K_n/K)$ such that

$$Q_n^\tau \equiv -\text{sign}(E, \mathbb{Q}) Q_n^\sigma \pmod{E(K_n)_{\text{tors}}},$$

where $\text{sign}(E, \mathbb{Q})$ is the root number of E .

Proposition 4.6. For each positive square-free integer n prime to the discriminant of \mathcal{O}_K , let $\{P_n\}$ be the collection of Heegner points attached to \mathcal{O}_n as in Definition 4.2. Then this collection of points form a Heegner system.

Proof. From Proposition 4.4, equation (7) and the discussion in between, the result follows quite formally. See for example [Gro91] Proposition 3.7 and Proposition 5.3 or [Dar04] section 3.4 and [GZ86] section II.1. \square

Once a Heegner System is constructed, Kolyvagin's machinery works and we get the following result.

Theorem 4.7 (Kolyvagin). *Let $\{Q_n\}$ be a Heegner system attached to (E, K) . If Q_1 is non-torsion then the following are true*

- *The Mordell-Weil group $E(K)$ is of rank one.*
- *The Shafarevich-Tate group of E/K is finite.*

Furthermore, the work of Gross-Zagier ([GZ86]) and Zhang ([Zha01, Zha04]) gives the nowadays classical result.

Theorem 4.8 (Gross-Zagier-Zhang). *The point Q_1 is non-torsion if and only if $L'(E/K, 1) \neq 0$.*

5. EXAMPLES

We want to show how our computations work in some concrete examples. The numerical computations are the following: first choose representatives \mathfrak{a}_i of the Class group of \mathcal{O} , and choose $\omega_i \in \mathcal{H}$ such that $\mathfrak{a}_i = \langle 1, \omega_i \rangle$ (as an element of the Class group). Then, as in the classical case, let M_{ω_i} be the order of matrices in $M_2(\mathbb{Z})$ that fixes ω_i , which is clearly isomorphic to \mathcal{O} . Each order contains a matrix N_i whose trace equals $\text{Tr}(\omega)$ and whose determinant equals $\text{Nm}(\omega)$. We search for matrices $A_i \in \text{SL}_2(\mathbb{Z})$ such that $A_i N_i A_i^{-1}$ belongs to $M_{ns}^{\varepsilon}(N) \cap M_0(m)$. Then the point $\tau_i = A_i \omega_i$ is a Heegner point for \mathcal{C} .

As discussed before, the matrices A_i are computed using the Chinese Remainder Theorem, via a local condition at the primes dividing $N^2 m$:

- At a prime p dividing m , we chose $A_i^{(p)}$ modulo $p^{v_p(m)}$ of determinant one, taking N_i to an upper triangular matrix. This can be done, since the roots of the characteristic polynomial of N_i are in \mathbb{F}_p (since every prime that divides m splits in \mathcal{O}), so we just take a basis of the Jordan form.
- At a prime p dividing N , since p is inert, the characteristic polynomial of N_i is irreducible in $\mathbb{F}_p[x]$. If $N_i = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$, then we want the matrix A_i to satisfy

$$A_i \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} = \begin{pmatrix} \frac{\alpha+\delta}{2} & \sqrt{\frac{d}{\varepsilon}} \\ \varepsilon \sqrt{\frac{d}{\varepsilon}} & \frac{\alpha+\delta}{2} \end{pmatrix} A_i \pmod{p}.$$

We just chose A_i as a matrix in 4 indeterminates and search for a non-zero solution of the system (the matrix determinant is zero, so there is always such a solution). If the determinant is not 1, we just multiply the matrix via an appropriate matrix, as in the proof of Lemma 1.2.

This gives us a matrix in $\text{SL}_2(\mathbb{Z}/N^2 m \mathbb{Z})$, and we lift it to a matrix in $\text{SL}_2(\mathbb{Z})$.

In Table 1 we give some examples of our method following the previous notation. All the examples were done using [PAR14]. The table notation is as follows: the first column is the elliptic curve label (in Cremona's notation), the next three columns show which primes of the curve are Supercuspidal, which ones are Steinberg and Principal series respectively. The next row gives the chosen ω (that determines the order in the imaginary quadratic field), and which primes are Cartan non-split ones (the remaining are classical ones). It is easy to see that in each example the Cartan Heegner condition is satisfied. Then we list the matrices A_i for some ε . The next column is for the first Fourier coefficient (where we use the notation $\zeta_i := \xi_N^i + \bar{\xi}_N^i$, and a vector $[a_1, \dots, a_N]$ means $a_1\zeta_1 + \dots + a_N\zeta_N$). Finally in the last column we have c , the Manin constant for the optimal quotient.

EC	Sc	St	Ps	ω	C_{ns}	A_i	b_1	c
121b	{11}	\emptyset	\emptyset	$\frac{1+\sqrt{-3}}{2}$	{11}	$\begin{pmatrix} 6 & -31 \\ 1 & -5 \end{pmatrix}$	$[-3, -1, -5, -4, 2]$	$\frac{1}{11}$
225a	{3, 5}	\emptyset	\emptyset	$\frac{1+\sqrt{-91}}{2}$	{3}	$\begin{pmatrix} 1 & -23 \\ 1 & 0 \end{pmatrix}$	1	1
				$\frac{3+\sqrt{-91}}{10}$	{3}	$\begin{pmatrix} 2 & -5 \\ 5 & -1 \end{pmatrix}$	1	
225a	{3, 5}	\emptyset	\emptyset	$\frac{1+\sqrt{-7}}{2}$	{3, 5}	$\begin{pmatrix} 8 & -58 \\ 1 & -7 \end{pmatrix}$	$\frac{1-\sqrt{5}}{2}$	1
289a	\emptyset	{17}	\emptyset	$\frac{1+\sqrt{-3}}{2}$	{17}	$\begin{pmatrix} 9 & -73 \\ 1 & 8 \end{pmatrix}$	$[-6, -7, -4, -1, -5, -2, -4, -5]$	$\frac{1}{17}$
1617a	\emptyset	{3, 11}	{7}	$\sqrt{-2}$	{7}	$\begin{pmatrix} 14 & -6 \\ 33 & -14 \end{pmatrix}$	$[-2, -1, -4]$	$\frac{1}{7}$
49a	{11}	\emptyset	\emptyset	$\frac{1+\sqrt{-11}}{2}$	{7}	$\begin{pmatrix} 4 & -15 \\ 1 & -3 \end{pmatrix}$	$\sqrt{-7}$	$\frac{1}{7}$

TABLE 1. Examples of the q -expansion and relates computational data

In Table 2 we show the points constructed on the curves of Table 1 and the multiple of the generator obtained (up to torsion). Note that in the last case, the curve has rank 0 over \mathbb{Q} , and this is why the point is not rational.

Remark 5.1. In all the examples of Table 1 but the last one, the optimal quotient coincides with the strong Weil curve. In the last example, the optimal quotient corresponds to the curve 49a2 in Cremona's notation.

APPENDIX A. THE PRINCIPAL SERIES CASE COMPUTATION

The purpose of this short Appendix is to show how the work [DD11] allows to, given an elliptic curve E with a ramified principal series at p , compute the character to twist by, and the local p -th Fourier coefficient of the forms h_i of Theorem 2.2.

EC	K	P	m_P
121b	$\mathbb{Q}(\sqrt{-3})$	$(\frac{2411156245}{(37062)^2}, -\frac{52866724475375}{(37602)^3})$	15
225a	$\mathbb{Q}(\sqrt{-91})$	$(1, 1)$	1
225a	$\mathbb{Q}(\sqrt{-7})$	$(-1, 0)$	2
289a	$\mathbb{Q}(\sqrt{-3})$	$(-\frac{15858973521095}{1083383^2}, -\frac{22895413346586388187}{1083383^3})$	3
1617a	$\mathbb{Q}(\sqrt{-2})$	$(\frac{3702}{17^2}, \frac{184078}{17^3})$	3
49a	$\mathbb{Q}(\sqrt{-11})$	$(\frac{1261982}{11(127)^2}, -\frac{680991}{11(127)^2} - \frac{327847275}{11^2(127)^3}\sqrt{-11})$	-

TABLE 2. Heegner points constructed

We thank Tim Dokchitser for explaining us some details of the algorithm. See the Example 5 of such article.

- (1) Compute $v_p =$ the valuation at p of the conductor of E . Then the order of the character is $\frac{12}{\gcd(12:v_p)}$. This number will be denoted by e .
- (2) Let $L = \mathbb{Q}(x)/(x^e - p)$. Then E attains have good reduction at the prime ideal (x) . Compute the characteristic polynomial $\chi_L(t) = t^2 - a_p t + p$ of Frobenius at such prime ideal by counting the number of points over the finite field (this is implemented in SAGE or Magma). The two roots are the p -th coefficients we are looking for (since there are 2 forms, conjugate to each other), but we need to match each root with its corresponding character.
- (3) Let g be a generator of \mathbb{F}_p^\times , and let $L' = \mathbb{Q}(x)/(x^e - g \cdot p)$. As before, compute the characteristic polynomial $\chi_{L'}(t)$ for the prime ideal (x) (the curve is again unramified). Then the product of a root of $\chi_L(t)$ multiplied by the correct character (evaluated at g) must be a root of $\chi_{L'}(t)$.

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